

AU/ACSC/AY2012

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

**LIGHTS OUT:
FORSEEABLE CATASTROPHIC EFFECTS OF GEOMAGNETIC
STORMS ON THE NORTH AMERICAN POWER GRID AND HOW
TO MITIGATE THEM**

by

Scott G. Smith, Major, USAF

Submitted to the Faculty
In Partial Fulfillment of Graduation Requirements

Advisor: Dr. Gregory F. Intoccia

Maxwell Air Force Base, Alabama

21 August 2011

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

DISCLAIMER

The views expressed in this academic research paper are those of the author and do not reflect the official policy or position of the US government or the Department of Defense. In accordance with Air Force Instruction 51-303, it is not copyrighted, but is the property of the United States government.

CONTENTS

DISCLAIMER	ii
ABSTRACT	iv
SECTION 1: INTRODUCTION	1
SECTION 2: BACKGROUND	4
Critical Infrastructure of the North American Power Grid	4
Large Area Threats to the Power Grid	5
Electromagnetic Pulses (EMP)	5
Geomagnetic Storms	7
SECTION 3: PROBLEM DESCRIPTION	9
Component Damage	9
Affected Areas	11
Power Restoration Estimates	13
SECTION 4: CONSEQUENCES	14
Short Term Outages	15
Long Term Outages	15
Power Outage Impact on Telecommunications and Internet Protocol Services	16
Power Outage Impact on Banking and Finance	17
Power Outage Impact on Petroleum and Natural Gas	17
Power Outage Impact on Transportation Infrastructure	18
Power Outage Impact on Consumables (Food, Water, Medication)	20
Power Outage Impact on Emergency Services	22
SECTION 5: POTENTIAL SOLUTIONS	25
Modifications to Protect Grid Infrastructure	25
Smart Grid Systems	26
Transformer Neutral Blocking Devices	29
Increase Warning Time Through Forecasting	30
Ensure Continuing Space Weather Forecasting	30
Increase Capabilities with State-of-the-Art and New Technology	31
Increase Power Restoration Capabilities	32
Stockpile Key Power Grid Infrastructure	32
Create Additional Capacity and Routing	33
SECTION 6: BEST SOLUTIONS COMPARED	33
Lead Time to Implement	34
Ability to Mitigate Effects	36
Cost	37
SECTION 7: CONCLUSION	39
Proposed Way Ahead to Protect America's Critical Infrastructure	40
Final Thoughts on the Unique Nature of This High Impact Low Frequency Event	42

ENDNOTES	44
BIBLIOGRAPHY	49

ABSTRACT

Failure of the North American Power Grid and subsequent long term disruption of reliable electricity service to a geographically large region can result in multiple second and third order effects with potentially enduring and devastating impact on American society. This paper focuses on the comprehensive effects of severe geomagnetic storms from solar events and discusses the best ways to protect, avert, and mitigate damage to the North American Power Grid. Using a problem solution methodology, it formulates several options and assesses them, examining their respective cost and ability to make the most immediate, direct impact on the protection of the North American Power Grid. Following this approach, it finds the installation of transformer neutral resistors as the best option for mitigation of the geomagnetic threat. As this solution would only offer 60 to 70 percent protection to the North American Power Grid, the paper also recommends increasing interconnections between subregions through nonsynchronous connections while continuing funding of solar environment forecasting in the short term. Additionally, it recommends investing in stockpiles of high voltage transformers and increasing funding for next generation solar forecasting research, development, and deployment in the long term. The final recommendation is the immediate creation of regional, state, and local emergency plans for long term power outages, to be exercised at regular intervals. This would enable the best protection for America's future power needs against the naturally occurring threat of geomagnetic storms, increase the survivability during an EMP event, and help maintain a normally functioning society in a long term power outage.



SECTION 1: INTRODUCTION

The North American Power Grid, made up of 157,810 miles of high voltage transmission lines, over 3000 high voltage transformers, and billions of dollars of investment, is extremely efficient at transmitting electricity over great distances. In fact, it is so proficient that large scale events capable of inducing harmful electrical currents through the power lines represent a significant threat to the infrastructure of the North American Power Grid.

Severe geomagnetic storms are a natural phenomenon able to produce damaging electrical effects and may be one of the most important, least understood threats to the North American Power Grid.¹ Critics argue these solar events have a low probability of occurring and discount the high consequences they produce based on a lack of historical examples. Yet in 1859, a solar flare produced a geomagnetic storm, called the Carrington event, which was many times greater than anything that has occurred since the electrical grid has been in place. A solar storm of this size, or even a smaller geomagnetic storm like the one that occurred on May 14-15 in 1921, could simultaneously knock out all of the power grids in the United States, Canada, northern Europe and Australia, with full recovery of the current power transmission capability requiring four to ten years.² Since the creation of the modern power grid, major power system impacts in the United States have occurred due to geomagnetic storms at least thirteen times between 1957 and 1991.³

Because most of the nation's critical infrastructure, such as telecommunications, banking, petroleum, natural gas, transportation, consumables (food, water, and medication), and emergency services, are so highly dependent on reliable power supply from the grid, a widespread and prolonged outage, can trigger unrest and a breakdown of social order, causing severe economic damage and threatening the very fabric of the United States. The threat to the

North American Power Grid is real. Steps to mitigate the effects of severe space weather, including better protection, resiliency, and improved space weather forecasting, must be taken to ensure the future of this critical infrastructure and the American way of life.

Given the reality that severe geomagnetic storms have occurred and can be expected to occur in the future, what are their foreseeable consequences and what actions should be taken to protect, avert, and mitigate damage to the North American Power Grid?

According to the North American Electric Reliability Corporation (NERC), “Geomagnetic Storm events have the potential to physically damage electrical and electronic equipment throughout North America’s critical infrastructure. The most significant electric reliability concern is the potential for simultaneous impact to large portions of the bulk power system, from which restoration and recovery may be challenging and prolonged.”⁴ Long term power outages through failure of the North American Power Grid would cripple other critical infrastructure causing catastrophic economic damage and social upheaval.

For this reason, the United States must act now to protect, avert, and mitigate damage to the North American Power Grid in the event of a geomagnetic storm. To prevent damage, funding for space weather forecasting needs to be continued in the short term and increased over the long term to improve forecasting capabilities. This would allow operators of the North American Power Grid to receive warnings of solar weather conditions capable of causing harm to critical components, giving operators time to remove them from the transmission network. While this would temporarily deny electricity to some consumers, it would protect long term power transmission capability. To avert damage, the Power Grid infrastructure should be protected with Smart Grid technology--including surge protectors, high speed switching circuits, and automated electricity flow controls which regulate power distribution across the system.

These improvements could be capable of preventing at least 70 to 75 percent of space weather-related power grid failures in the event the United States was hit by the equivalent of the great geomagnetic storms of 1859 and 1921.⁵ To mitigate damage, or quickly restore power to affected areas and minimize adverse effects, components critical to the Power Grid should be stockpiled as insurance against failure or damage from solar storms while cultivating domestic production capacity of such infrastructure. Currently, the worldwide waiting list for high voltage transformers is about three years with most production capacity residing outside the United States.⁶

Additionally, national, state, county, city, and individual emergency plans must be created to address widespread and long term power outages. The Federal Emergency Management Agency (FEMA) has no published plan for a long term loss of power on a national or regional scale, nor do most lower levels of state and local government, based on searches of FEMA.gov and other government sources. These are essential due to the critical nature of the power supply and the second and third order effects that widespread, long term failure of the North American Power Grid would have on American society as a whole.

The measures previously described would mitigate the effects of solar storms, make the Power Grid more resilient, and speed recovery from critical failures. With the creation of emergency action plans, the United States would also strengthen its ability to respond to other catastrophic events resulting in long term power transmission failure, such as a terrorist attack, natural disaster, or war.

This paper focuses on the effects of severe geomagnetic storms and discusses the best ways to prevent, avert, and mitigate the outcome of these occurrences. This is based on the most cost effective measures balanced against those able to make the most immediate impact on the

protection of the North American Power Grid. The solutions suggested enable the best protection for America's future power needs against the naturally occurring threat of severe space weather and will increase survivability during an electromagnetic pulse (EMP) event.

This research paper uses the problem-solution methodology to describe the severity, scope, and effects of severe geomagnetic storms. Next, solutions are compared based on lead time to implement, cost, and ability to avert, mitigate, and protect the North American Power Grid. The best of these solutions are highlighted based on the previous criteria. Finally, recommendations are made on how to implement the selected solutions to provide a viable way forward in light of the threat posed by severe solar storms.

SECTION 2: BACKGROUND

Critical Infrastructure of the North American Power Grid

According to Executive Order 13010 signed in 1996, certain national infrastructures are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States. While not a new concept (having appeared in some form in many of the policy debates in the 1980s), Order 13010 did break new ground in listing what it considered to be critical infrastructures, including electrical power systems.⁷

Electrical power is arguably the most important of the critical infrastructures because all of the others are so highly dependent on reliable power supply from the grid. Figure 1 pictorially illustrates the interdependencies between many of the identified critical national infrastructures; of particular note is the central role held by the Power Grid which ties all the entities together and allows them to function. The information age has increased our reliance on electricity, making electric power supply central to the sustained operation of the Nation's other critical infrastructures.⁸

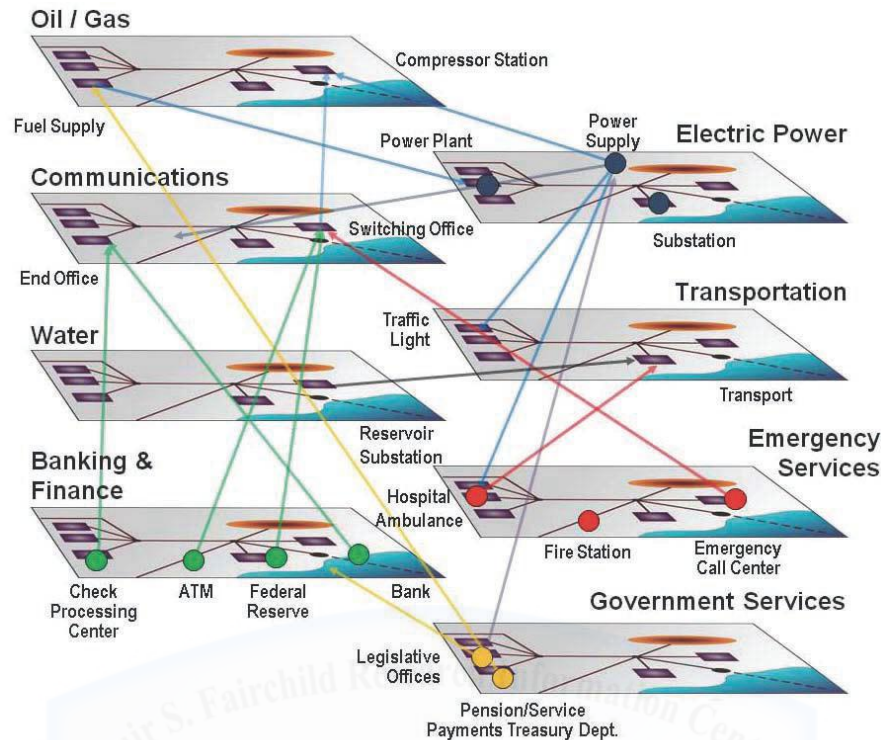


Figure 1-Interconnected infrastructures and their qualitative dependencies and interdependencies.⁹

Large Area Threats to the Power Grid

As a critical component in our nation's infrastructure, the North American Power Grid is designed to be flexible, with the inherent ability to quickly restore power due to localized faults or small scale disruptions. Large area threats to the Power Grid are unique, creating the potential for damage in thousands of critical components simultaneously over areas encompassing multiple states. Based on the scope of projected damage on a national level, the widespread nature of electromagnetic pulses and severe geomagnetic storms has the capability to shut down the entire North American Power Grid.

Electromagnetic Pulses (EMP)

The term "EMP" has been used since the late 1960s to describe the electromagnetic pulse generated by a nuclear detonation.¹⁰ Nuclear weapons produce localized effects on electronic

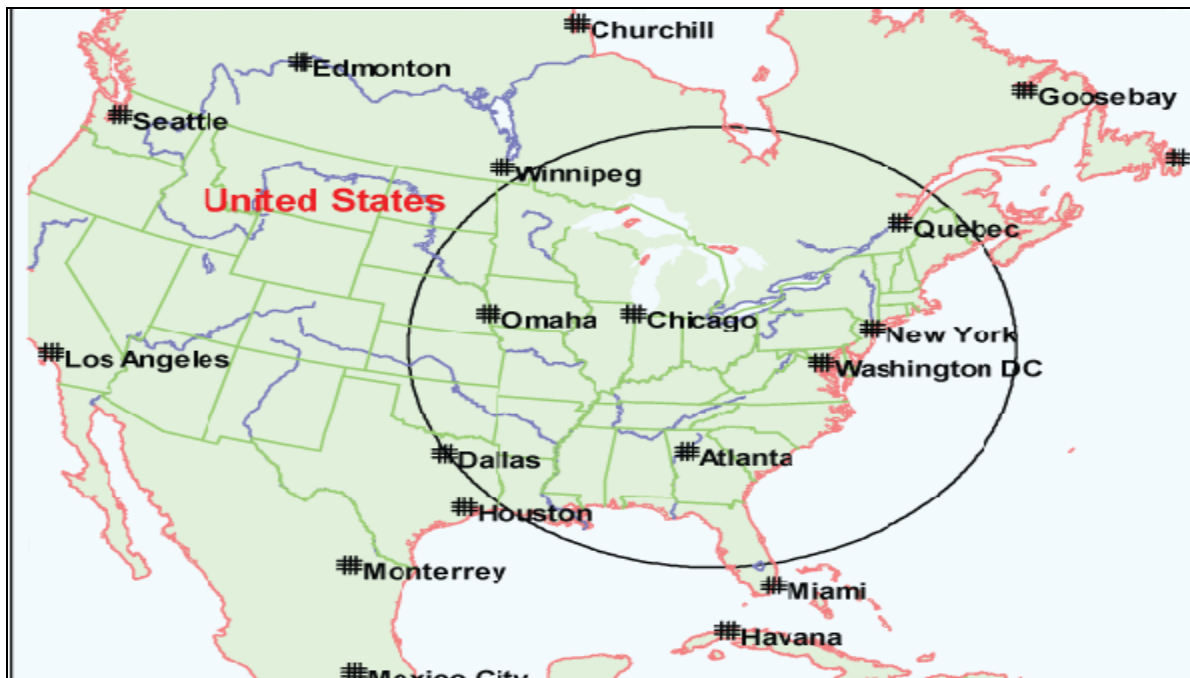


Figure 2-Exposure area for EMP burst at 170 km over Ohio¹¹

devices in an area approximated by the blast radius, but in the case of a high altitude burst, the EMP effects are magnified over greater distances.

Electromagnetic pulses from a nuclear blast are divided into three categories by waveform, commonly referred to as E1, E2, and E3, for which natural electromagnetic equivalents exist. These waveforms induce electrical flows through mediums capable of conducting electricity, such as overhead power lines, phone and signal lines, and power supply cords, a process referred to as coupling. The E1 waveform's electromagnetic field is very similar to that generated near an electrostatic discharge. It couples efficiently to short lines (1-10 meters) connected to equipment (power, signal lines, etc.), can induce large voltages and currents able to be conducted inside equipment (computers, radios, etc). It also couples efficiently to overhead power lines, producing high currents and voltages dangerous to distribution line insulators and transformers.¹² In comparison, the E2 waveform produces an electromagnetic field similar to a lightning strike, dissipating rapidly as distance from the source increases. It is

unlikely that E2 fields could pose a problem for power lines as the induced voltages are not expected to be very high.¹³ The E3 waveform is nearly identical to the fields created by a geomagnetic storm, lasting from a few to hundreds of seconds.¹⁴ Both the E1 and E3 waveforms couple efficiently with the North American Power Grid and induce current and voltage capable of damaging associated infrastructure and disrupting power transmission on a broad scale based on the nuclear blast characteristics.

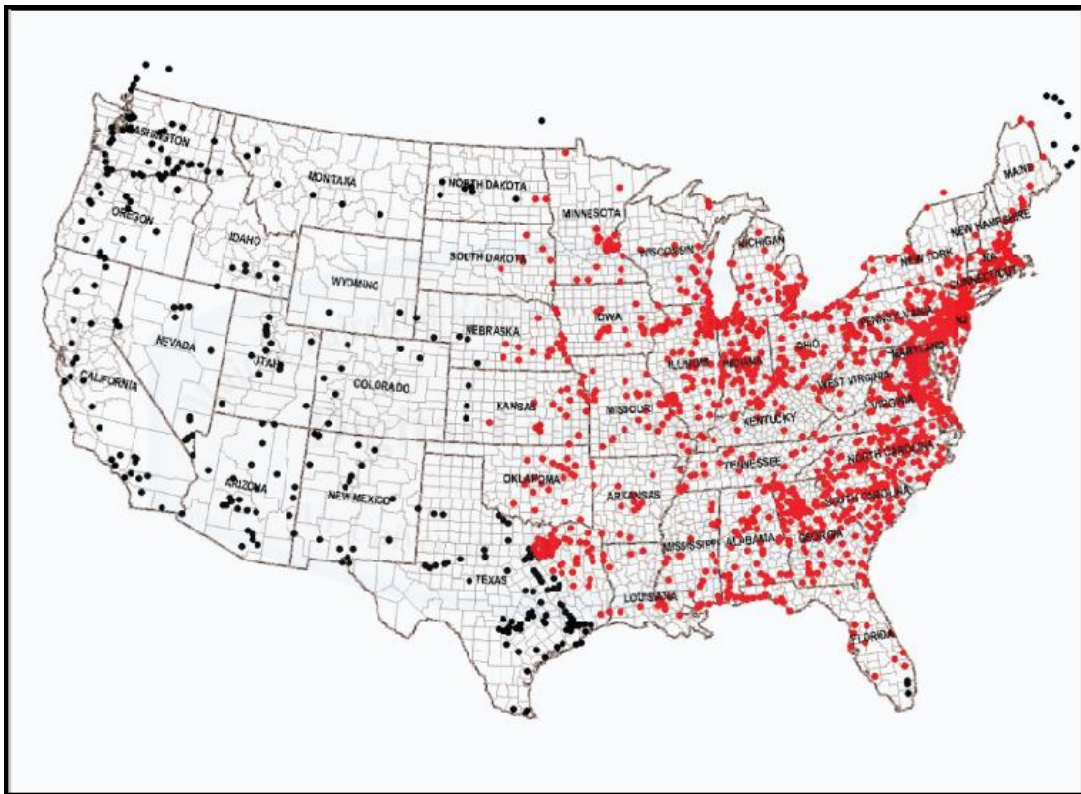


Figure 3-1765 Extra High Voltage substations at 345 kiloVolt and higher (83%) exposed by the burst in Figure 2.¹⁵

Geomagnetic Storms

Another threat capable of causing widespread failure in the North American Power Grid is a severe solar storm. Intense solar activity, particularly large solar flares and associated coronal mass ejections can create disturbances in the atmosphere when this activity is directed towards the Earth. The coronal mass ejection's solar wind plasma connects with the magnetosphere causing rapid changes in the configuration of Earth's magnetic field, a form of

space weather called a geomagnetic storm. Geomagnetic storms produce impulsive disturbance of the geomagnetic field over wide geographic regions which, in turn, induce currents (called geomagnetically-induced currents or GIC) in the North American Power Grid and other high-voltage power systems in the affected area through power lines.¹⁶

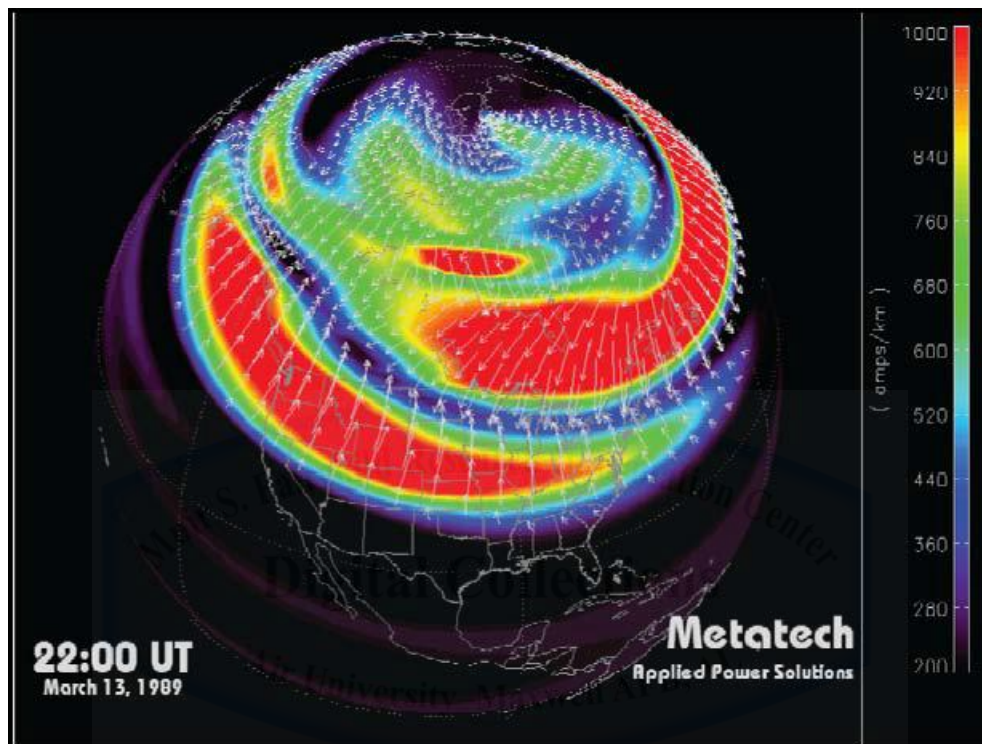


Figure 4-Synoptic map of geomagnetic field disturbance conditions at 22:00UT (17:00EST), March 13, 1989¹⁷

Geomagnetic storms occur regularly as part of the solar weather pattern. Sun spot activity is seasonal, with solar maximums occurring every ten to fifteen years. While severe geomagnetic storms are more likely to coincide with increased sunspot activity, large solar flares have occurred outside these solar maximums. Figure 5 below shows all recorded geomagnetic storms between 1933 and 2006 in red, with solar activity in blue.

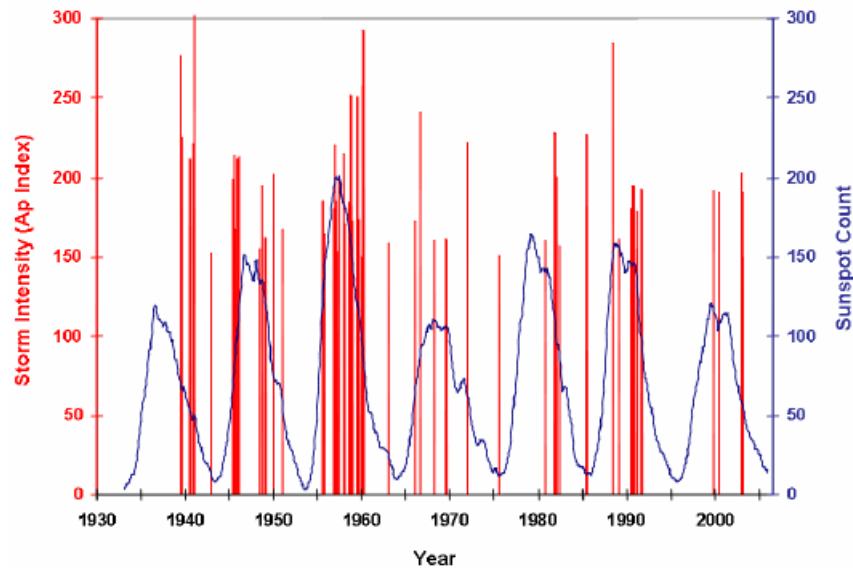


Figure 5-All major geomagnetic storms from September 1933 through 2006¹⁸

Severe geomagnetic storms, like the Carrington event in 1859 and the May 1921 storm are commonly referred to as one hundred year storms. These storms, the two strongest on record, would be off the storm intensity scale if included on the graph above. Geomagnetic storms are a way of life and part of the natural cycle of the sun. The primary concern to the North American Power Grid is the intensity and geographic area affected by severe solar weather.

SECTION 3: PROBLEM DESCRIPTION

Large area threats to the North American Power Grid could damage a significant portion of its critical components at the same time. This would result in failure of the Power Grid over large geographical areas. Subsequent blackouts could last for an extended period of time based on expected timelines to replace damaged critical components. Enduring Power Grid failures affecting considerable portions of the population are the primary problem posed by large area threats.

Component Damage

EMP and geomagnetic storms have the potential to physically damage electrical and electronic equipment throughout North America's critical infrastructure from induced currents,

efficiently carried by the 157,810 miles of high voltage transmission lines. A key component in the system particularly at risk is the high voltage transformer, referenced in Figure 6 as a generator step-up transformer. These components convert relatively low voltage power produced at generation sites and raise it to the higher voltages required for efficient transmission across the country. Transformers experience excessive levels of internal heating brought on

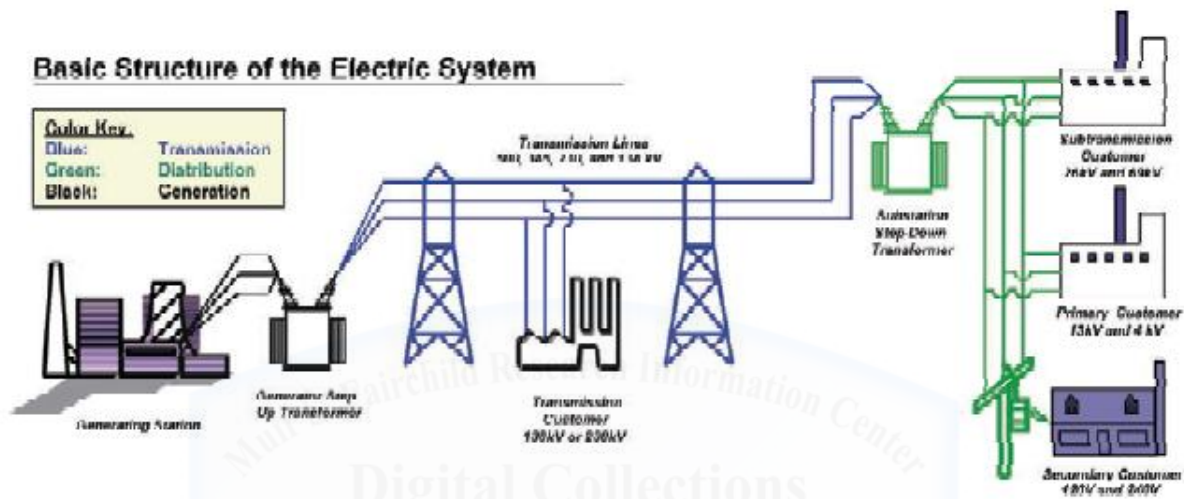


Figure 6-Power system overview¹⁹

when induced currents cause the transformer's magnetic core to saturate and vent excess heat outside the normal core steel magnetic circuit. This also causes depressed system voltages, failures or misoperation of critical system voltage control devices, and damage to the transformers themselves.²⁰ Previous cases have noted heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers, such as the March 1989 Geomagnetic Storm shown in Figure 7. These transformers generally cannot be repaired in the field, and if damaged in this manner, need to be replaced with new units, which have manufacturing lead times of 12–24 months or more in the world market.²¹



Figure 7-Salem, NJ Nuclear Plant Generator Step-Up Transformer and permanent damage caused by the March 13, 1989 Geomagnetic Storm.²²

Affected Areas

The North American Power Grid is designed to be robust. Failure nodes are removed from the rest of the system until they can be returned to normal operation, usually with no electricity interruption to the consumer. This provides some risk mitigation against localized threats, like single transformer or power line damage, but leaves the system vulnerable to widespread failures. In an event with a large geographical foot print like a geomagnetic storm, the danger to the Power Grid is that many transformers and other critical equipment would all be exposed to the same induced currents and have the potential to fail simultaneously. Research has shown that failure of only four percent of the nodes in a high load scenario may cause up to sixty percent loss of connectivity. This four percent figure shrinks to two percent when specifying a cascading failure of nodes, resulting in the same connectivity loss.²³ These interruptions realized across the North American Power Grid would translate into widespread power failures through only a few affected critical locations. Additional research has shown that GIC may contribute

significantly to transformer failures on large transmission systems, like the North American Power Grid, in the mid-latitude regions of the continental United States, where GICs are generally thought not to be significant.²⁴

Figure 8 illustrates the transmission nodes across the North American Power Grid and their projected survivability during a geomagnetic storm affecting the same area as the March 1989 storm, but ten times stronger, roughly the same magnitude of the May 1921 storm, the second largest in recorded history. The red areas represent nodes that have either failed or have been removed from the system as a result of geomagnetic storm damage. Nodes still in operation are depicted by green circles. The areas outlined in black project areas where some connectivity would still exist, but power transmission would be disrupted due to system collapse from cascading failures. Also important to note is that the figure below does not project power outages at the consumer level. Limited localized power transmission capability may be available,

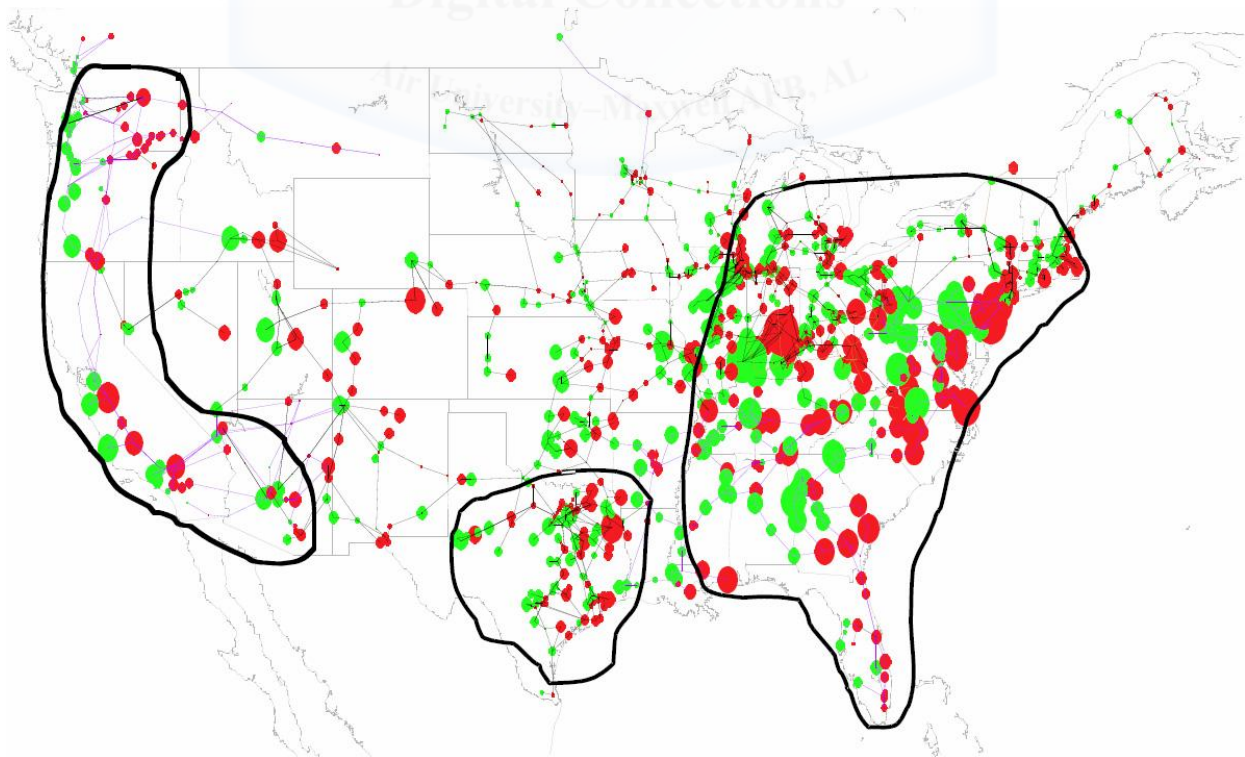


Figure 8-Areas of potential system collapse from a geomagnetic storm 10 times stronger than the March 1989 Event²⁵

but the remaining operational nodes noted in green outside the black circles clearly show a majority of the population would be without power across the greater part of the United States.

Power Restoration Estimates

Projections of the event depicted above also indicate that the induced current in over 350 of the 2000 highest voltage transformers would exceed levels where they are at risk of irreparable damage, leading to prolonged restoration and long-term chronic shortages of electrical supply capability to the impacted regions, arguably for multiple years.²⁶ This extended time frame is primarily due to the long lead time required to produce high voltage transformers. These transformers are the critical link (1) between generation and transmission, (2) within the transmission network, (3) between the transmission and distribution systems, and (4) from the distribution to the consumer.²⁷ Under normal conditions, the purchase placement of a single transformer order in the 300-400MVA class has normally been quoted as taking up to 15 months for manufacture and test.²⁸ For larger sizes of transformers and those with special requirements, the suitability of qualified manufacturers may be more limited, requiring extension of the associated lead time by several months. Logistical concerns regarding the time to transport, install, and configure such equipment could exceed an additional 12 months in some cases.²⁹

Rapid recovery of the power grid without these key transformers would not be possible. Even retrofitting damaged areas using a small transportable transformer design may not be applicable to replace the very large capacity transformers.³⁰ If portions of the system were able to be reconfigured with smaller transformers, this would limit the distance reliable power could be transported. Electricity gradually drops in voltage when transmitted over long distances, therefore transmitting power with lower starting voltage limits the distance over which the desired end voltage can be produced.³¹ Since production locations are historically displaced

from population centers for environmental and habitation concerns, distribution would be limited due to the lack of transmission capability from failed high voltage transformers, rendering power production almost irrelevant. In the event of widespread failures from geomagnetic storms, local electricity may be restored in areas co-located with power plants, but system-wide restoration to most US consumers, who are dependent on high voltage transformers, would be measured in years, not months.

SECTION 4: CONSEQUENCES

The primary consequence of a severe geomagnetic storm would be disruption of reliable electricity service to the majority of the United States through widespread damage to high voltage transformers and other critical components of the North American Power Grid. The functioning of society and the economy is critically dependent upon the availability of electricity. Essentially every aspect of American society requires electrical power to function. Contemporary U.S. society is not structured, nor does it have the means, to provide for the needs of nearly 300 million Americans without electricity.³² Continued electrical supply is necessary for sustaining water supplies, production and distribution of food, fuel, communications, and everything else that is a part of our economy. Continuous, reliable electrical supply is a critical element to the continued existence and growth of the United States and other developed countries. For most Americans, production of goods and services and most of life's activities stop during a power outage. Not only is it impossible to perform many everyday domestic and workplace tasks, but also people must divert their time to dealing with the consequences of having no electricity. In the extreme, they must focus on survival itself. The situation is not different for the economy at large. No other infrastructure could, by its own collapse alone, create such an outcome.³³ As the most vital of our Nation's critical infrastructures, removing

electric power from the interdependency chart in Figure 1 would leave a gaping hole as it affects every other infrastructure listed. Likewise, power transmission and distribution is also dependent on many of the other areas listed. These interdependencies compose a complex system where removing one would have multiple second and third order effects on all the others.

Short Term Outages

The impact of a short term power outage would be severe but not catastrophic if the recovery was rapid or the geographic impact sufficiently limited. The recovery times from previous large-scale outages have been on the order of one to several days. This record of quick recovery is attributable to the remarkably effective operation of protective systems and communications that are an essential part of the power infrastructure and the multiple sources of replacement components from surrounding systems not impacted.³⁴ For example, on August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. The outage affected an area with an estimated 50 million people in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey and the Canadian province of Ontario. The blackout began a few minutes after 4:00 pm Eastern Daylight Time (16:00 EDT), and power was not restored until four days later in some parts of the United States. Parts of Ontario suffered rolling blackouts for more than a week before full power was restored. Estimates of total costs in the United States range between \$4 billion and \$10 billion (U.S. dollars).³⁵ In this context, a geomagnetic storm creating a short blackout scenario over a relatively small geographic region would be economically painful, but present no threat to national survival.

Long Term Outages

A geographically widespread blackout due to a severe geomagnetic storm that involves

physical damage to thousands of components may produce a persistent outage that would far exceed historical experience, with potentially catastrophic effect. Simulation work sponsored by the Commission at the National Infrastructure Simulation and Analysis Center (NISAC) has suggested that, after a few days, what little power production that does take place would be offset by accumulating loss of perishables, collapse of businesses, loss of the financial systems and dislocation of the work force. The consequences of lack of food, heat (or air conditioning), water, waste disposal, medical, police, fire fighting support, and effective civil authority would threaten society itself.³⁶

Power Outage Impact on Telecommunications and Internet Protocol Services

To offset a loss of electric power, telecommunication sites use a mix of batteries, mobile generators, and fixed-location generators. These are prioritized based on the importance of the site, ranging from a cell tower site having a battery backup usable for approximately three hours to a major telecommunications facility having an on-site generator capable of supplying power while maintenance and fuel supplies existed. Backup power supplies range from 4 to 72 hours available on-site and would depend on either the resumption of electrical utility power or fuel deliveries to function for longer periods of time.³⁷ A majority of residential telephones today depend on power from local central offices, which would be lost once the backup power at those locations runs out. Cellular phones would be an option as long as their batteries remain charged and the cellular tower network's battery backups still functioned, but most power supplies for these services would be depleted within days. Thus, callers' ability to access 9-1-1 call centers would be a major concern in an extended power outage situation. Data networks and internet service would experience the same losses based on functional backup power. Loss of electricity would eventually lead to a long-term loss of telecommunications and internet protocol services

in extended geographic areas that would cascade to critical applications, such as banking and finance, petroleum and natural gas flow regulation, transportation, and emergency services, that all depend on these communication services.³⁸

Power Outage Impact on Banking and Finance

The financial network is highly dependent on power and telecommunications for normal operations. Widespread power outages would shut down the network and all financial activity. ATM transactions, stock trading, and online and local banking, would cease until power was restored, similar to the blackout caused by Hurricane Katrina, resulting in a staggering economic loss that is still an enormous drain on the national economy.³⁹ Modern banking depends almost entirely on electronic data storage and retrieval systems for record keeping and to perform account transactions. A severe geomagnetic storm that damages the power grid over a widespread geographical area would render banking transactions virtually impossible as a practical or legal matter.⁴⁰ In the immediate aftermath of widespread power failure, banks would find it very difficult to operate and provide the public with the liquidity they require to survive; that is, to buy food, water, gas, or other essential supplies and services. Nonfunctioning ATM machines, for example, and other impediments to obtaining cash might well undermine consumer confidence in the banking system and cause a panic. The alternative to a disrupted electronic economy may not be reversion to a 19th century cash economy, but reversion to an earlier economy based on barter.⁴¹

Power Outage Impact on Petroleum and Natural Gas

Petroleum and natural gas systems are heavily dependent on commercial electricity and telecommunication services during the entire cycle of production, refining, processing, transport, and delivery to the consumer. The availability of commercial power is the most important

dependency for the domestic oil sector.⁴² The natural gas infrastructure depends on electric power to operate lube pumps for compressors, after-cooler fans, electronic control panels, voice and data telecommunication, computers, communication and controls infrastructure, gas control centers, and other critical components. Telecommunications systems are used for the direction of personnel and equipment, the control and synchronization of multiple geophysical acoustical signal sources for oil and gas exploration, and the telemetering of geophysical data. Mobile radio plays a critical role in providing communications for the management of individual wells, pipeline gathering systems, and in the transfer, loading, and delivery of petroleum products to end user consumers. In the event of emergency conditions, communication systems are essential to ensure the safety of personnel, the adjacent population, and the surrounding environment.⁴³

Petroleum and natural gas infrastructures are generally well equipped with gas-driven compressors and gas- or diesel-fired pumping facilities and backup generators that would enable the continued flow of natural gas, crude oil, and refined product deliveries for a limited time or that would implement a controlled shutdown following an interruption of electric power supply. Outages of a few days or more can be expected to severely affect all petroleum and natural gas infrastructure operations when backup power systems fail due to lack of fuel deliveries.⁴⁴

Power Outage Impact on Transportation Infrastructure

The transportation infrastructure, consisting of railroad, passenger and commercial vehicles, maritime shipping, and aviation, are all heavily dependent on commercial power and telecommunications for normal and efficient operations. Ground transportation relies on the electric grid that runs pipelines and pumping stations for gasoline, and powers signal lights, street lights, switching tracks, and other electronic equipment for regulating traffic on roads and rails. Aviation and maritime transportation rely on commercial power that runs radar, radios,

and traffic control systems. While some short term backups are available, most transportation infrastructure would be severely impacted by power outages over broad geographic regions lasting for more than a few days.

Centralized railroad control centers, as well as operations throughout the rail system, use extensive communication networks for automated sensing, monitoring, and control. If a railroad control center becomes inoperable due to a blackout or loses communications with the rail network for any reason, all rail traffic in the affected domain would stop until communications are restored or backup procedures are implemented.⁴⁵ The major effect of power failures to railroad signal controls would be delayed traffic. If commercial power is unavailable for periods longer than approximately 24 hours, degraded railroad operations would persist under manual control while locomotive fuel supplies and battery backups remain intact or commercial power is restored.⁴⁶

Failure of electronically based traffic control signals would exacerbate vehicular traffic congestion in metropolitan areas. With modern traffic patterns, even a very small number of disabled vehicles or accidents can cause debilitating traffic jams.⁴⁷ In the aftermath of a geographically widespread blackout due to a severe geomagnetic storm that occurs during working hours, a large number of people taking to the road at the same time to try to get home could expect extreme traffic congestion. After the initial traffic congestion has subsided, the reconstitution of the automobile and trucking infrastructures in the event of a widespread power loss would depend primarily on two factors—the availability of fuel and commercial power.⁴⁸ Vehicles need fuel to operate and service stations need electricity to power fuel pumps. Few service stations possess backup generators, which would create spikes in fuel prices as demand rapidly exceeds supply in the short term. Most consumers would be left with only the fuel in

their vehicles at the onset of the power loss to see them through its duration. Interstate commerce would essentially shut down and transporting aid supplies to affected areas would become problematic. Replenishing the fuel supply and restoring commercial power would pace the return to normal operations.⁴⁹

Aviation and maritime shipping share the same dependencies on electrical power and telecommunication systems for effective control of the airspace or maritime mediums, while the vehicles rely on fuel deliveries to operate. Power to all critical components of the Federal Aviation Administration system is backed by fuel generator power, and in some instances, through temporary use of large, battery operated power supplies.⁵⁰ This may allow some aviation activities to take place while fuel supplies to backup generators exist. Similarly, ships could still enter ports so long as the on-site backup generators for traffic control have fuel, but dockside loading and unloading rely on operation of the North American Power Grid. Port cranes capable of handling large cargo containers using commercial power have no backup systems in place. Thus, loading and unloading of containers would stop until commercial power is restored.⁵¹

Power Outage Impact on Consumables (Food, Water, Medication)

Agricultural operations for growing all major crops requires large quantities of water, usually supplied through irrigation or other artificial means using electric pumps, valves, and other machinery to draw or redirect water from aquifers, aqueducts, and reservoirs. Farm machinery runs on gasoline and petroleum products supplied by pipelines, pumps, and transportation systems that run on electricity or that depend on electronic components. Egg farms and poultry farms typically sustain dense populations in carefully controlled environments using automated feeding, watering, and air conditioning systems. Dairy farms rely heavily on

electrically powered equipment for milking cattle and for making other dairy products. These are just a few examples of how modern food production depends on the electric power grid.⁵² Food processing also requires electricity. Cleaning, sorting, packaging, and canning of all kinds of agricultural products are performed by electrically powered machinery. Butchering, cleaning, and packaging of poultry, pork, beef, fish, and other meat products also are typically automated operations, done on electrically driven processing lines.⁵³

Food and medical distribution also depends heavily on electricity. Vast quantities of vegetables, fruits, and meats are stored in warehouses, where they are preserved by refrigeration systems, ready for distribution to supermarkets. Refrigerated trucks and trains are the main means of moving perishable foods and medication to market; therefore, distribution also has a critical dependence on the infrastructure for ground transportation. Because markets typically carry only enough food and medication to supply local populations for 1 to 3 days and need to be resupplied continually from regional warehouses, transportation and distribution of food and medical supplies to markets may be the weakest link in the food infrastructure and represents a serious threat to public safety from lack of medicines.⁵⁴ Federal, state, and local agencies combined would find it difficult to cope immediately or even over a protracted period of days or weeks following a geomagnetic storm that causes the food infrastructure to fail across a geographic area encompassing one or more states. The infrastructure failure at the level of distribution that is likely during a severe geomagnetic storm could bring on food and medicine shortages affecting the general population in as little as 24 hours.⁵⁵

The electric power grid also provides the energy that runs the water infrastructure. A geomagnetic storm that disrupts or collapses the power grid would interrupt or stop the operation of the electrical machinery in the water infrastructure. Some water systems have emergency

power generators, which could provide continued — albeit greatly reduced — water supply and wastewater operations for a short time.⁵⁶

Commercial stores typically stock enough consumable liquids to supply the normal demands of the local population for 1 to 3 days, although the demand for water and other consumable liquids would greatly increase if tap water were no longer available or unsafe. Local water supplies would quickly disappear. Resupplying local stores with water would be difficult in the aftermath of a geomagnetic storm that disrupts transportation systems, a likely condition if all critical infrastructures were affected. Federal, state, and local emergency services, faced with the failure of the water infrastructure in a single large city, would be hard pressed to provide the population with the minimum water requirements necessary to sustain life over a time frame longer than a few days.⁵⁷ They could not provide, on an extended emergency basis, the water requirements and services, including waste removal, necessary to sustain normal habitation and industrial production in a single large city. A severe geomagnetic storm could disrupt the water infrastructure over a large geographic area encompassing many cities for a protracted period of weeks or even months.⁵⁸

A prolonged water shortage may quickly lead to serious consequences. People preoccupied with finding or producing enough drinking water to sustain life would be unavailable to work at normal jobs. Demoralization and deterioration of social order can be expected to deepen if a water shortage is protracted. Anarchy would certainly loom if government cannot supply the population with enough water to preserve health and life.⁵⁹

Power Outage Impact on Emergency Services

Americans have come to rely on prompt and effective delivery of fire, police, rescue, and emergency medical services through local government systems, backed up by state capabilities

(e.g., state police and National Guard) and specialized capacities such as those provided by the Department of Homeland Security, the Department of Justice, the Centers for Disease Control and Prevention, and other federal entities. Emergency services at all levels are receiving increased emphasis as a consequence of 9/11, but the main focus over the past decade has been preventing and responding to terrorism.⁶⁰

Unfortunately, little emergency services planning considers long term or widespread power failure, much less an enduring power failure over a vast geographical area caused by a severe geomagnetic storm. The demand for emergency services would almost certainly increase dramatically in the aftermath of a widespread blackout. Demands within the context of blackouts fall into two broad categories: *information* and *assistance*. The absence of timely information and the inability of recovery actions to meet the demand for emergency services would have grave consequences.⁶¹

Emergency rescue services can be expected to experience an increase in demand. People trapped on subways and in elevators would require timely rescue. If electric power is interrupted for any period of time, people at home that depend on oxygen concentrators, respirators, aspirators, and other life-sustaining equipment that require electric power would need to find alternative solutions quickly. If power is out for more than several days, people dependent on dialysis machines, nebulizers, and other life-supporting medical devices would also be placed at risk. Finally, inability to replenish home supplies of medicines would eventually lead still more people to depend on emergency services.⁶²

Police services would be stretched extremely thin for several reasons. Foreseeably, police could be called on to assist rescue workers in removing people from immediate dangers. Failures of traffic control systems resulting in traffic jams would generate demands for police

traffic management services. Antisocial activities are also possible following a chaotic event. If looting or other forms of civil disorder erupt, it is possible for local police services to become overwhelmed. In that event, deployment of National Guard forces, imposition of curfews, and other more drastic measures could become necessary.⁶³

When the failure of police and emergency services becomes protracted, the lawless element of society may emerge. For example, Hurricane Katrina in August 2005 damaged cell phone towers and radio antennas that were crucial to the operation of emergency communications. Protracted blackout of the local power grid caused generators supporting emergency communications to exhaust their fuel supplies or fail from overuse. Consequently, government, police, and emergency services were severely impacted in their ability to communicate with the public and with each other.⁶⁴ Looting, violence, and other criminal activities were serious problems in the aftermath of Katrina. A geomagnetic storm induced blackout is likely to overtax generators supporting emergency communications, cell phone towers, and radio antennas for a protracted period, creating the same conditions that incited lawless behavior in the aftermath of Katrina.⁶⁵

A key aspect of protecting lives and economic resources in an extended, widespread power failure would be the creation of national and regional emergency plans for area wide blackouts. According to the *National Response Framework*, incidents must be managed at the lowest possible jurisdictional level and supported by additional capabilities when needed.⁶⁶ Due to the interconnections of the Power Grid and the widespread nature of the threat, local and state emergency plans would be simply inadequate to address the scope of infrastructure failures caused by a severe geomagnetic storm. After only a few days when backup power sources expire, very little coordination with outside agencies could occur. Regional and federal

emergency plans should be created and practiced to ensure that interstate and federal resources are available to afflicted areas and to improve coordination of relief efforts during initial response times when backup sources still provide power. With the creation of emergency action plans, the United States would also strengthen its ability to respond to other catastrophic events resulting in long term power failure, such as a terrorist attack, natural disaster, or war.

Long term power outages across a broad geographical area due to failed high voltage transformers are the primary consequence of a severe geomagnetic storm. The loss of reliable electricity service would dramatically impact every other critical infrastructure and would alter the fabric of American society after only a few days. Millions of lives and trillions of dollars are at risk of these natural occurrences whose effects could be averted and mitigated, protecting the North American Power Grid and society as a whole.

SECTION 5: POTENTIAL SOLUTIONS

Several methods exist for protecting the North American Power Grid from severe geomagnetic storms. Critical components can be protected from the induced currents conducted through power lines through use of smart grid systems and transformer neutral blocking devices. They can also be removed from the Power Grid to prevent damage if there is enough warning through solar weather forecasting. Despite the best efforts to prevent damage to electrical infrastructure, some components are likely to fail in a severe solar storm. To mitigate damage to the North American Power Grid, key components should be stockpiled while creating additional capacity and routing. These actions would allow for rapid restoration of electrical service in the event of damage, restricting power losses to short durations and small geographic areas.

Modifications to Protect Grid Infrastructure

Arguably, the most comprehensive way to prevent harmful effects to the North American

Power Grid and its transformers is to prevent geomagnetically induced currents (GIC) from being conducted over transmission lines. Hydro Quebec has spent more than \$1.2 billion since 1989 installing transmission line series capacitors, which block GIC flows over its 18,600 miles of transmission line.⁶⁷ Eliminating induced currents from geomagnetic storms over the 157,810 miles of high voltage transmission network in the North American Power Grid would cost tens of billions dollars and take years to install. Significantly cheaper and less time consuming methods are available to protect the North American Power Grid infrastructure.

Smart Grid Systems

The North American Power Grid continues to evolve as new technology is developed. Though smart grid systems are designed to improve the efficiency and automation of power transmission and distribution from generation to the customer, several applications provide inherent capabilities to prevent and mitigate damage from geomagnetic storms. One effect of great numbers of automation components interacting with a Smart Grid is distributed decision making. Equipment and smart-grid subsystems share actionable information so that localized decision making not only serves local self-interest, but collaboratively supports the overall health of the system.⁶⁸ As individual components of the system fail, including processing and communications components, the remaining connected components would have the ability to adapt and reconfigure themselves to best achieve reliable electricity transmission and distribution, much like a society of devices.⁶⁹

Distributed decision making is supported through increased situational awareness of grid behavior provided by wide-area-measurement networks. Phasor measurement units (PMUs) identify and analyze system vulnerabilities in real time, and can detect evolving disturbances in the region's bulk electric system.⁷⁰ Time-synchronized, high quality measurements allow

reliability coordinators and balancing authorities to make informed decisions based on area wide concerns, not just local conditions. The North American Synchro-Phasor Initiative (NASPI), led by NERC and supported by the Department of Energy (DOE), is advancing the coordination of the deployment of PMUs and the networking of their measurements for wide-area situation awareness and other applications, a key capability that would make the North American Power Grid better able to withstand a geomagnetic storm.⁷¹

Another Smart Grid system capable of mitigating damage would be to expand the capability of the system to break into islands of matching load and generation, enhancing what now exists to minimize the impact of geomagnetic storms and provide for more rapid and widespread recovery in the event of power loss. Currently, there are only three interconnections in the North American Power Grid: Western, Eastern, and ERCOT (Figure 8). This greatly increases areas affected by damage and power loss in the event of a severe geomagnetic storm.

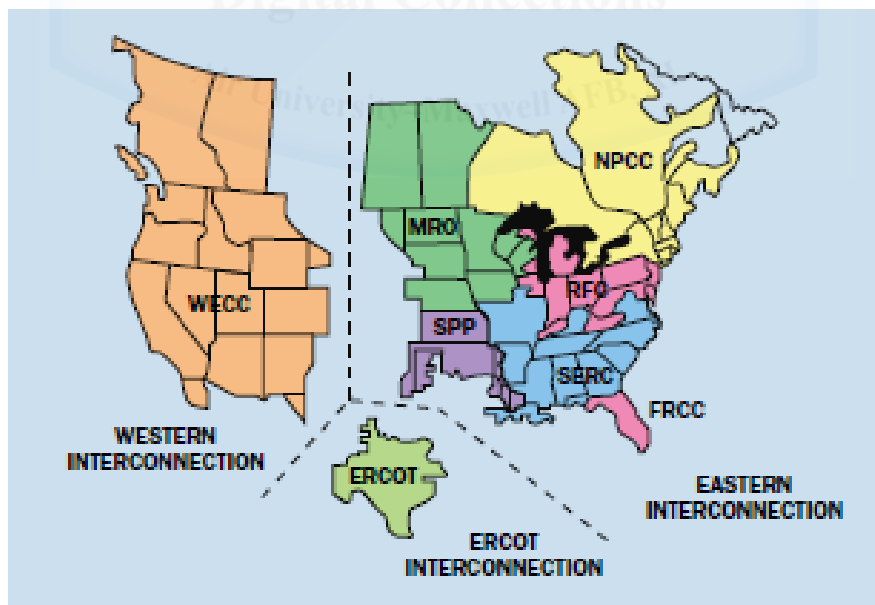


Figure 8-Current North American Power Grid interconnections and North American Electric Reliability Corporation (NERC) regions⁷²

The establishment of nonsynchronous connections between subregions should be required. At a minimum, using the NERC regions in Figure 8 would improve the Power Grid's resiliency to a large area threat, while using the more robust Environmental Protection Agency (EPA)

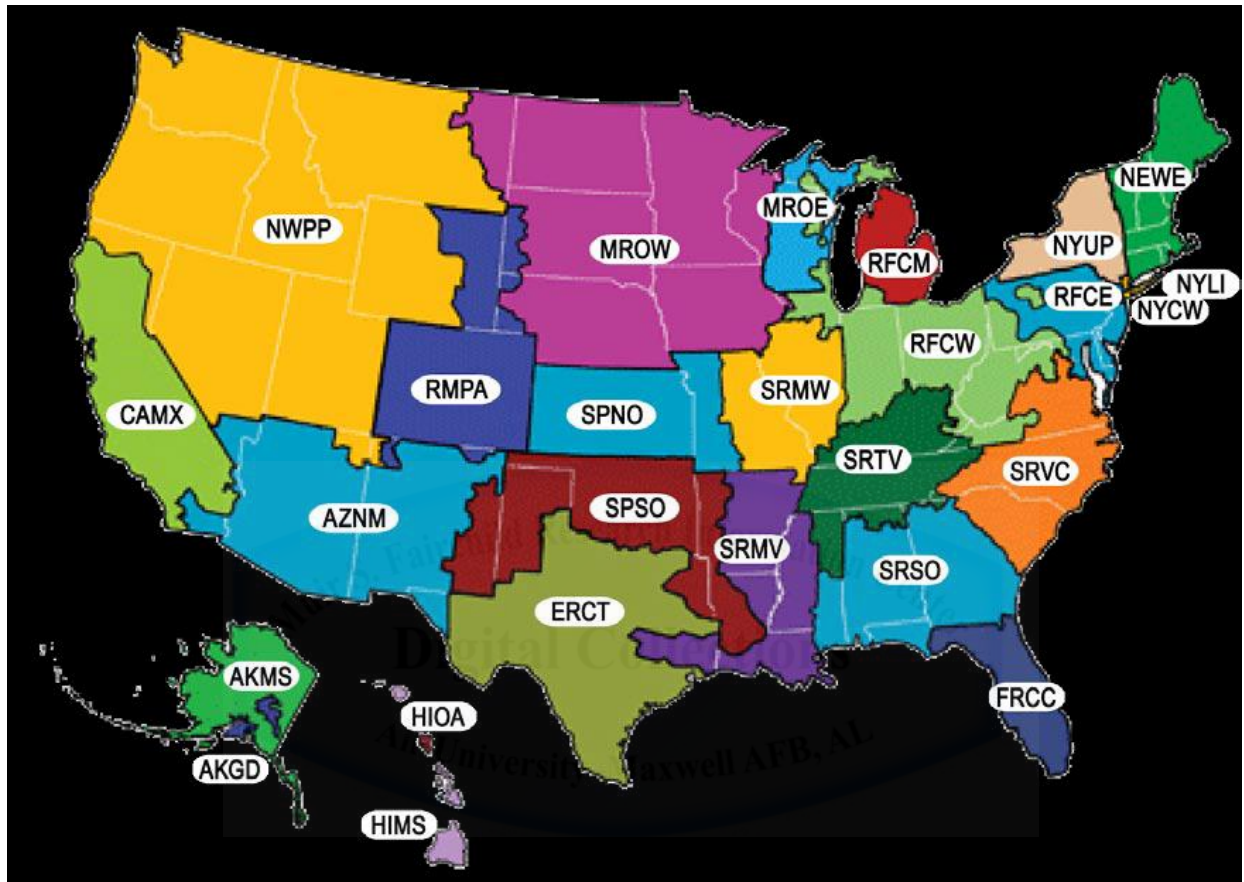


Figure 9-Environmental Protection Agency (EPA) Emissions and Generation Resource Integrated Database (eGRID) regions⁷³

Emissions and Generation Resource Integrated Database (eGRID) model in Figure 9 would maximize protection beyond the Eastern Interconnection. This can readily be accomplished today with approaches such as DC back-to-back converter installations that facilitate power transfers but maintain a barrier.⁷⁴ Breaking the larger electrical power system into subsystem islands of matching load and generation will enhance what now exists to minimize the impact, decrease the likelihood of broad, system wide collapse, and provide for more rapid and widespread recovery in the event of a severe geomagnetic storm. The islanding of the system

through nonsynchronous connections may also help reduce geomagnetic storm impacts by shortening long power line coupling in some instances.⁷⁵ It is just as useful for normal reliability against random disturbances or other natural disasters in reducing the size and time of blackouts. Ensuring this islanding capability is critical for protection and restoration of the North American Power Grid from the threat of severe geomagnetic storms.⁷⁶

Transformer Neutral Blocking Devices

Protection of critical components in power generation and transmission is also critical to prevent large scale power failures due to the effects of geomagnetic storms. Priority for protection is on the highest voltage, highest power units serving the longest lines. These require the most time to replace, are the most vulnerable, and provide the major flow and delivery of power.⁷⁷ Provisions must be made for the protection of large high-value assets such as transformers and breakers. This could include adding either permanent or switchable resistance to ground in the neutral of large transformers.⁷⁸ This protection would then be available upon notice of the onset of a solar storm, thus it provides a simple expedient that does not compromise performance under normal operation. Due to the interconnected nature of the grid and to the need for that connectivity to enable recovery, the likelihood of a blackout lasting years over large portions of the affected region is substantial with damage to these high-value components.⁷⁹

The transformer neutral blocking strategy is the global application of a simple resistor with low electrical resistance (low-ohmic resistor) in the neutral-to-ground connection point in all transformers on the power grid. This approach would only achieve partial reduction in geomagnetically induced currents (GIC), but is balanced with the trade-off being a simple, more reliable, and overall less-expensive Power Grid hardening solution than other forms of GIC protection. Devices using this approach can typically reduce overall GIC levels by 60 to 70

percent.⁸⁰ Transformer neutral blocking resistors also have inherent cost advantages, in that the devices can be built to withstand lower voltage and current ratings compared to in-line installation options. Also because the resistance is added in the neutral, where currents are normally at or near zero, the power system would not be exposed to higher operating losses due to added resistance in each AC phase line.⁸¹ These devices could protect critical assets in the North American Power Grid and avert damage due to severe geomagnetic storms.

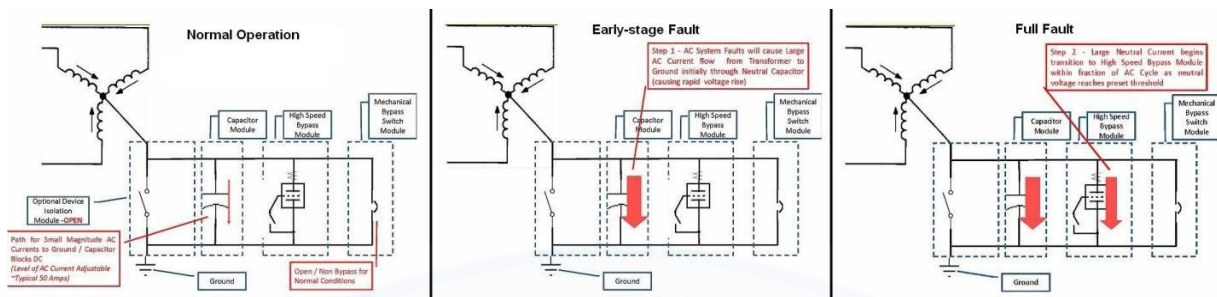


Figure 10- Kappenman GIC Neutral Blocking Device⁸²

Increase Warning Time through Forecasting

Ensure Continuing Space Weather Forecasting

Space weather forecasting provides vital warning in the event of geomagnetic storms that can be used to remove components from current flows and protect critical infrastructure. The North American Power Grid has operational procedures to put in place in times of geomagnetic storms. It has prepared actions conducted from advanced forecasts as well as actions carried out from near-term forecasts and updates on a continuous basis.⁸³ For example, with fifteen minutes advance notice units could be quick-started, generation could be increased or decreased based on predicted effects, transformers could offload voltage to reduce heating, and key facilities could be manned with operators to switch off a transformer if they see it overloading.⁸⁴ Advanced notice is provided from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) or from commercial providers that depend greatly on SWPC

data to provide even more detailed forecasts of what could occur. This data is primarily provided by the European Space Agency's Solar and Heliospheric Observatory (SOHO) and the

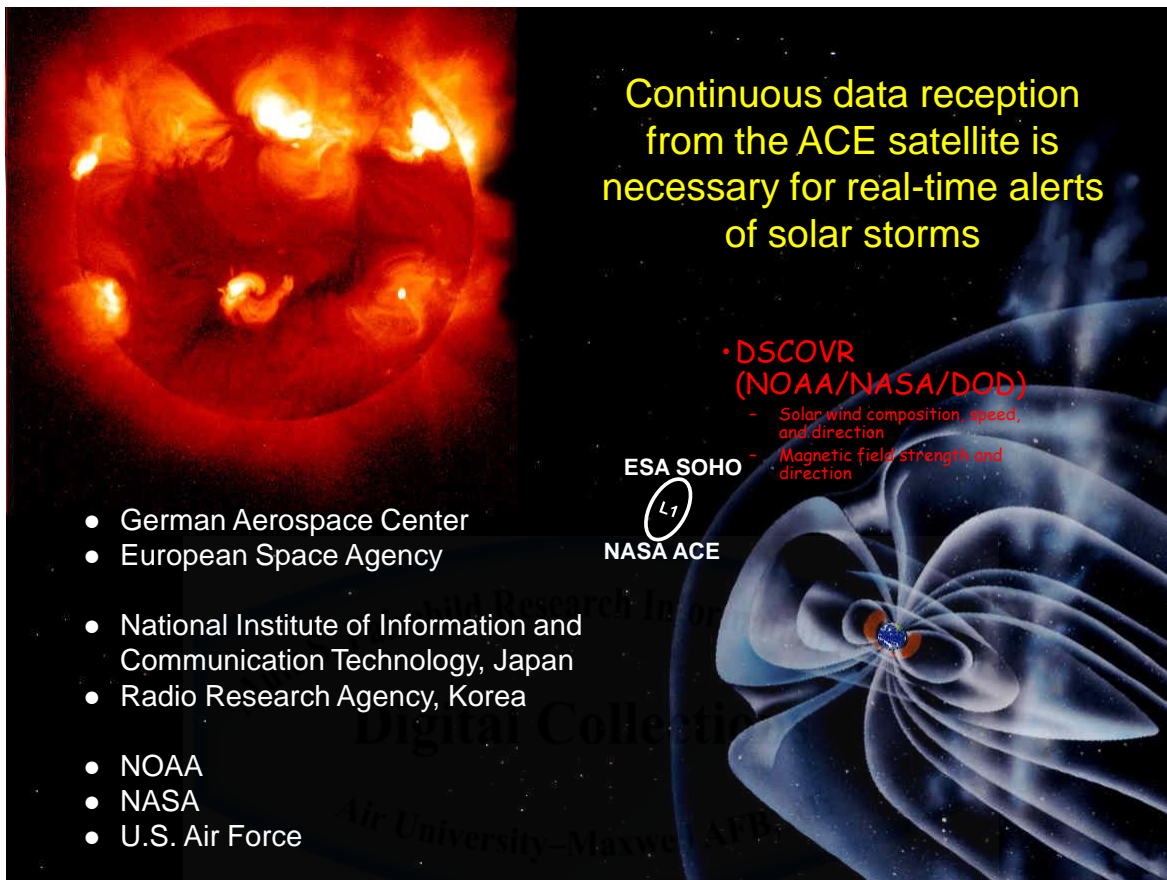


Figure 11-Positioning of solar weather early warning satellites and their users⁸⁵

National Aeronautics and Space Administration's (NASA) Advanced Composition Explorer (ACE). These forecasts are a critical element in the fifteen to forty-five minute warnings used to protect the North American Power Grid. Without continued NOAA and NASA funding for these capabilities, the associated warnings would be lost.

Increase Capabilities with State-of-the-Art and New Technology

Current solar weather monitoring platforms have exceeded their design life, leaving no source for the critical data they gather should failure occur. Launched in 1997, ACE is powered by solar cells, giving the spacecraft a design life of at least five years.⁸⁶ Currently it is operating

nine years past its engineering specification. SOHO is also well past its design life of two years, having been launched in 1995.⁸⁷

The replacement platform designated for ACE and SOHO is a joint NOAA/NASA/US Air Force refurbishment of the Deep Space Climate Observatory (DSCOVR) spacecraft as a space weather mission. Society's reliance on technology that is vulnerable to space weather events makes it necessary to refurbish DSCOVR which will provide data to support timely and accurate forecasts and warnings of geomagnetic storms. This interagency partnership is the most expeditious and cost effective option for making DSCOVR operational in time for the approaching Solar Maximum and unreliable life cycle expectancy of aging ACE and SOHO spacecraft.⁸⁸ Funding for this program in addition to research and development on new technology designed to increase warning time of severe solar weather capable of producing geomagnetic storms and increase the accuracy of these predictions must be continued. This would allow deployment of DSCOVR on time in 2013 and continue development of emerging technology capable of improving space weather forecasting. These steps would ensure data flow necessary for space weather forecasting and advance warning of geomagnetic storms continue, allowing for increased protection of the North American Power Grid.

Increase Power Restoration Capabilities

Stockpile Key Power Grid Infrastructure

Key components of the Power Grid, especially high voltage transformers, have a high potential to fail during severe geomagnetic storms.⁸⁹ The large footprint of such storms could cause geographically widespread power failures over large parts of the United States. To minimize the duration of these blackouts, key power grid infrastructure needs to be stockpiled to provide replacement equipment for failed components. Such reserves would be readily available

to substitute for damaged components and could significantly reduce power grid repair time, specifically for components with long lead times, like the 12 – 24 months required for most high voltage transformer applications.⁹⁰ In the case of larger transformers, stockpiles would need to be kept on site due to the added logistical complications incurred from their size. With replacement units available and in place, power grid failures could be reduced in duration and scope. Without stockpiled critical components, blackouts from severe geomagnetic storms would be of an extended duration and area and could have catastrophic consequences due to additional critical infrastructure failures.

Create Additional Capacity and Routing

In addition to the increased islanding of the North American Power Grid through nonsynchronous connections, additional capacity and routing should also be created to help mitigate the effects of severe geomagnetic storms. The existing electrical system at peak demand periods increasingly operates at or near reliability limits of its physical capacity.⁹¹ Modern electronics, communications, protection, control and computers have allowed the North American Power Grid to operate close to its maximum capability, leaving ever smaller margins of error to ensure reliable electricity delivery to the consumer. Therefore, a relatively modest upset to the system could cause functional collapse when operating near maximum capacity.⁹² The threat of exceeding system reliability limits from the high operating levels of the Power Grid can be mitigated by adding additional power transmission capacity and routing. These actions would increase the margin of error and reduce operating levels comfortably below reliability limits. The improved resiliency would also facilitate accelerated power restoration in the case of blackouts during geomagnetic storms.

SECTION 6: BEST SOLUTIONS COMPARED

Each of the potential solutions discussed was compared on a relative scale and assigned a value in descending order from six to one, with six being the best score possible. The comparisons focused on lead time to implement, ability to mitigate the effects of geomagnetic storms, and overall cost. Although each solution suggesting an improvement or modification to the North American Power Grid involves engineering trade-offs that need to be clearly understood, most could be incorporated into ongoing modernization efforts with overall positive impacts on the system.

Lead Time to Implement

The next solar maximum is expected to significantly increase solar activity in 2013. Therefore, the lead time necessary to implement the suggested solutions could be the key factor in preventing a catastrophic Power Grid failure. Continued space weather forecasting is the solution with the least amount of required lead time because the only additional item needed is funding.

Modifying the nature of the grounding of the entire North American Power Grid by adding transformer neutral blocking devices for geomagnetically induced current (GIC) reduction does not appear to pose significant or insurmountable impediments despite a change in the overall system. As long as transformer neutral resistors are appropriately used, they do not appear to alter the grounding coefficients of the North American Power Grid beyond the Institute of Electrical and Electronics Engineers' (IEEE) guideline recommendations.⁹³ This technology is readily available and can be retrofitted to any critical Power Grid infrastructure, and has the second lowest lead time to implement.

Of the six solutions presented, Smart Grid systems have the next lowest time to implement. This modernization of the North American Power Grid infrastructure with Smart Grid systems will take years overall, but if improvements are made with survivability and resiliency in mind, future upgrades should improve the reliability of the Power Grid in extreme geomagnetic environments. The islanding of the system through nonsynchronous connections can readily be accomplished today with approaches such as DC back-to-back converter installations that facilitate power transfers but maintain a barrier between connections. This approach could eliminate large service interruptions while still maintaining the present interconnection status.⁹⁴ Although converter installation would require a longer term system design and implementation, the capability is just as useful for normal reliability against random disturbances, natural disasters, or terrorist attacks in reducing size and time for blackouts.⁹⁵

Developing new space weather forecasting capabilities would also require years to research, develop, and deploy, but could provide enhanced warning of severe geomagnetic storms. This could foster the development of new techniques and procedures to better mitigate adverse effects of GIC and prevent damage to critical components.

Creating additional capacity and routing is another potential long term solution. Over 36,000 miles of transmission lines are projected to be added in the next ten years, with 35 percent of the additions directly benefiting the reliability of the North American Power Grid.⁹⁶ These additions should improve the function of the bulk power system, but may not provide enough of a reduction over system-wide demand levels to avoid Power Grid limitations during severe geomagnetic storms. Additional transmission capacity would need to be added to reach these levels of reduced demand, increasing the lead time to implement threshold beyond ten years in the future.

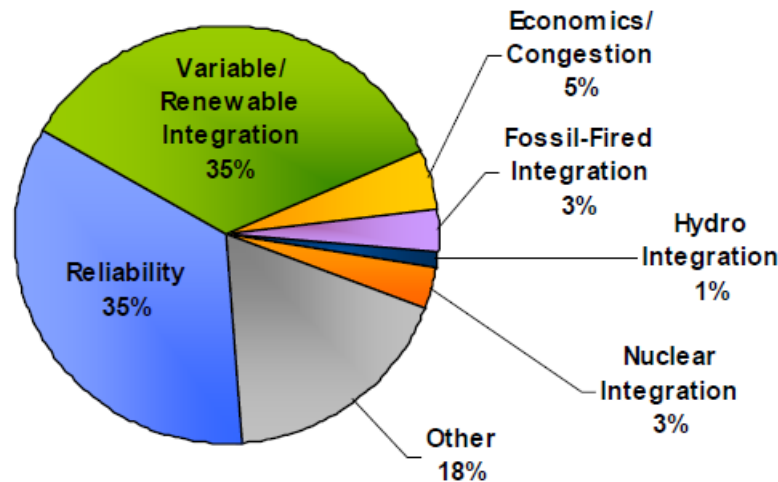


Figure 12- Relative transmission mile additions >200 kV by primary driver⁹⁷

Finally, timelines necessary to stockpile key infrastructure could also exceed a decade. The current U.S. replacement rate for the 345 kV and higher voltage transformers is 10 per year, with worldwide production capacity of these units at less than 100 per year.⁹⁸ Due to lead times of 12 – 24 months, creating a comprehensive stockpile for the 3000 – 5000 transformers at risk could require at 30 – 50 years at current production levels. Even a smaller stockpile of only the most critical applications would still conceivably require more than 10 years.

Ability to Mitigate Effects

The large footprint of severe geomagnetic storms present unique challenges associated with mitigation of adverse effects across the entire North American Power Grid. The solution best able to mitigate the effects of geomagnetically induced current (GIC) is the installation of transformer neutral blocking resistors in every transformer in the Power Grid. This approach would reduce GIC flows by 60 to 70 percent and would prevent damaging transformer overloads in most cases.⁹⁹

The next best option to mitigate the effects of a severe geomagnetic storm is the installation of Smart Grid systems, especially the increased islanding of the Power Grid through nonsynchronous connections. This approach would help confine blackouts to smaller regions

and would promote more rapid restoration of electrical power. Stockpiling critical infrastructure, like high voltage transformers, would also help reduce the duration of blackouts and is the third best solution to mitigate the effects of severe geomagnetic storms.

Creating additional transmission capability and routing to help decrease demand system wide would move the operating level of the North American Power Grid away from reliability limits. This would decrease the effect of a severe geomagnetic storm on the Power Grid and represents the fourth best solution.

Space weather forecasting also has the capability to help mitigate the effects of GIC on the Power Grid through advance warning. Using this prior notice, grid operators can manage system configurations and voltage load to help prevent damage to infrastructure and associated blackouts. In the case of a severe geomagnetic storm, the footprint of the storm capable of damaging equipment would be large enough to significantly reduce operators' ability to manage adverse effects through system configurations. Because of this issue, existing and future space weather forecasting have the lowest ability to mitigate the effects of a severe geomagnetic storm, although they do offer some protection during storms of lower intensity or that cover smaller geographic areas. Future forecasting capability was given the higher score of the two because future advance warning capabilities could provide more options to Power Grid operators than are currently available.

Cost

The most cost effective solution to mitigate the effects of severe geomagnetic storms is the installation of transformer neutral blocking resistors. With a cost per unit of \$40,000 to \$100,000 each, outfitting each of the 3000 to 5000 transformers in the Power Grid would cost between \$250 million and \$500 million.¹⁰⁰ With over 100 million households purchasing

electricity from the North American Power Grid, this could easily be funded through a one-time surcharge of \$5 or less per household electricity bill, a sum easily afforded by all.

Continuing funding for current space weather forecasting is also cost effective, receiving the second best score. In 2005, space weather activities at the National Oceanic and Atmospheric Administration (NOAA) became part of the local warnings and forecast line item that is funded at about \$850 million annually.¹⁰¹ New space weather forecasting capabilities will require similar operating budgets, plus research and development capital in addition to actual hardware costs. For example, the NOAA budget for fiscal year 2012 includes a \$47.3 million request for the Deep Space Climate Observatory (DSCOVR) to initiate the refurbishment of the DSCOVR spacecraft as a space weather mission in time for a 2013 launch.¹⁰² With costs around \$1 billion annually, new space weather forecasting is the third most cost effective solution.

Adding additional transmission capacity and routing has the next lowest cost to mitigate adverse effects from geomagnetic storms. At the rate of \$1 million per mile or more, adding enough additional capability to have a system wide effect quickly becomes significant, with one thousand miles costing at least \$1 billion.

Smart Grid systems are also significantly expensive. For perspective, the US Department of Energy 2009 Smart Grid System Report estimates that it may take as much as \$1.5 trillion to update the North American Power Grid with Smart Grid technology by 2030.¹⁰³ While this figure includes many initiatives beyond the scope of this research, significant costs in the billions of dollars will be incurred to equip the Power Grid to support distributed decision making and increase the number of islands in the system through nonsynchronous connections, making it the second least cost effective solution.

The most expensive solution explored is stockpiling critical Power Grid infrastructure.

At the cost of \$10 million per large transformer, stockpiling over 1000 of the largest transformers would cost more than \$10 billion.¹⁰⁴

While none of these solutions presented are inexpensive, all have the potential to reduce adverse effects from severe geomagnetic storms. The comparison is summarized in Table 1. Installing transformer neutral blocking devices provides the cheapest solution with the best

Best Solutions Compared				
Solution	Lead Time to Implement	Ability to Mitigate Effects	Cost Effectiveness	Total
Smart Grid Systems	4	5	2	11
Transformer Neutral Blocking Devices	5	6	6	17
Continuing Space Weather Forecasting	6	1	5	12
New Forecasting Capabilities	3	2	4	9
Stockpile Infrastructure	1	4	1	6
Additional Capacity/Routing	2	3	3	8

Table 1-Relative comparison of best solutions to mitigate effects of severe geomagnetic storms on the North American Power Grid

ability to mitigate adverse effects in the least amount of time. Continuing space weather forecasting is the next best solution, followed by installation of Smart Grid systems to facilitate distributed decision making and increased intelligent islanding through nonsynchronous connections between regions. Developing new forecasting abilities, adding transmission capacity and routing, and stockpiling critical infrastructure round out the remaining solutions.

SECTION 7: CONCLUSION

Geomagnetic storms are a regularly occurring, natural result of solar activity that has frequent impacts on the North American Power Grid. The severity of the impact on the Power Grid grows with increases in geomagnetic storm intensity, duration, and affected area. A severe geomagnetic storm could cause the failure of large portions of the North American Power Grid simultaneously. Damage to hundreds of critical components, especially high voltage

transformers, would extend recovery times beyond the capability of currently installed backup power sources. When these backups fail, collapse of the telecommunications, banking, petroleum, natural gas, transportation, consumables (food, water, and medication), and emergency service infrastructure would soon follow. The cumulative result of a severe geomagnetic storm causing an extended, widespread failure of the North American Power Grid would be catastrophic economic damage and social upheaval sufficient to threaten the fabric of the United States.

Methods to protect, avert, and mitigate damage from severe geomagnetic storms to the North American Power Grid are cost effective and available today. The best solution is the installation of transformer neutral blocking devices on every transformer in the Power Grid. Funding also needs to be continued to support the National Oceanic and Atmospheric Administration's Space Weather Forecasting Center, which provides advance warning of geomagnetic storms. Another effective solution is the continued installation of Smart Grid systems, especially those that facilitate distributed decision making while increasing the number of islands in the system through nonsynchronous connections between regions. Developing new forecasting abilities, adding transmission capacity and routing, and stockpiling critical infrastructure can also help protect and mitigate damage to the North American Power Grid from severe geomagnetic storms.

Proposed Way Ahead to Protect America's Critical Infrastructure

Preventing blackouts, or limiting the duration and affected area, is critical during a severe geomagnetic storm. To best accomplish this, a comprehensive approach should be taken to ensure the resiliency of the North American Power Grid. First, Congressional legislation or regulation from the Federal Energy Regulatory Commission (FERC) should require the

installation of transformer neutral blocking devices on all transformers in the Power Grid, including new additions. Second, the current North American Power Grid interconnections should be increased from 3 to 22 regions through nonsynchronous connections using the Environmental Protection Agency's (EPA) Emissions and Generation Resource Integrated Database (eGRID) model. Both of these solutions should be completed by the end of 2013 to prepare for the approaching Solar Maximum and expected increase in sun spot activity. These methods would reduce geomagnetically induced currents (GIC) by 60 to 70 percent¹⁰⁵ and reduce the area and duration of blackouts caused by severe geomagnetic storms.

Legislation or regulation should also include provisions to require purchasing replacement transformers at a two to one rate, so that a new transformer can replace the old while establishing a critical infrastructure stockpile in a less capital intensive manner. Additional provisions should also be included to incentivize building increased transmission capacity and routing infrastructure beyond system requirements for added reliability. Regulation and oversight would also need to be maintained to ensure Smart Grid upgrades promote Power Grid reliability and resiliency while introducing no new system vulnerabilities.

The Federal Emergency Management Agency (FEMA) and the United States Department of Energy (DOE) should also be required to create national and regional emergency plans for events resulting in widespread, extended power failures. These should be practiced at regular intervals to facilitate better coordination and survivability during severe geomagnetic storms. With the creation of emergency action plans, the United States would also strengthen its ability to respond to other catastrophic events resulting in widespread power transmission failure, such as a terrorist attack, natural disaster, or war.

Finally, the US government must understand the importance of space weather forecasting

in efforts to avert and mitigate damage from severe geomagnetic storms. Funding should be continued for current NOAA Space Weather Prediction Center budgets and programs.

Additionally, continued funding should be obligated for the Deep Space Climate Observatory (DSCOVR) follow-on solar observation spacecraft. Increased funding for research, development, and deployment of next generation space weather forecasting capabilities should also occur.

These solutions and suggestions are the most cost effective methods to prevent, avert, and mitigate damage to the North American Power Grid from a severe geomagnetic storm in the least amount of time. This threat is real and requires immediate action to avert a nightmare scenario from which the United States currently has little protection. These infrastructure solutions and the creation of national emergency plans will not only protect the Power Grid from geomagnetic storms, but will also increase the resiliency and reliability of every day operations and in the case of terrorist or cyber-attacks, natural disasters, or war.¹⁰⁶ Additionally, based on the similarity of the electromagnetic pulse (EMP) E3 waveform and GIC, North American Power Grid protection efforts would reduce the impacts of E3 effects during an EMP event.

Final Thoughts on the Unique Nature of This High Impact, Low Frequency Event

High impact, low frequency (HILF) events are typically dismissed because cost benefit analyses usually do not justify the significant expenditure of resources to counter an incident that has a low chance of occurring, given the laws of probability. Severe geomagnetic storms, commonly referred to as 100-year storms, are typically grouped into this category. To place them in the HILF category is to ignore history and discount scientific opinion. The Carrington event in 1859 and another storm on May 14-15, 1921 are two historical examples of 100-year, severe geomagnetic storms on record. These events have been given a high probability (near 100 percent) of occurrence by the Electric Infrastructure Security Council and others.¹⁰⁷ To ignore or

marginalize the threat posed by severe geomagnetic storms invites disaster on a national scale.

Swift action is required to protect the North American Power Grid and the American way of life.



Notes

All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.

¹ House, *What is Space Weather*, 36.

² Emanuelson, “Nuclear Electromagnetic Pulse.”

³ House, *What is Space Weather*, 36.

⁴ North American Electric Reliability Corporation (NERC), *Executive Brief*, 1.

⁵ Lawrence, “Solar ‘Katrina’ Storm.”

⁶ EMP Commission, *Critical National Infrastructures*, 27.

⁷ Moteff and Parfomak, *Critical Infrastructure and Key Assets*, 7.

⁸ House, *What is Space Weather*, 39.

⁹ EMP Commission, *Critical National Infrastructures*, 10.

¹⁰ NERC and U.S. DOE, *High Impact, Low Frequency Event*, 77.

¹¹ *Ibid.*, 82.

¹² *Ibid.*, 81.

¹³ *Ibid.*

¹⁴ *Ibid.*

¹⁵ *Ibid.*, 83.

¹⁶ *Ibid.*, 61.

¹⁷ *Ibid.*, 67.

¹⁸ Kappenman, *Geomagnetic Storms and Their Impact*, 3-2.

¹⁹ EMP Commission, *Critical National Infrastructures*, 21.

²⁰ NERC, *1989 Geomagnetic Storm*, 40.

²¹ NERC and U.S. DOE, *High Impact, Low Frequency Event*, 70.

-
- ²² Ibid., 71.
- ²³ Albert et al., *Structural Vulnerability of the Power Grid*, 7 - 8.
- ²⁴ Gaunt and Coetzee, "Transformer Failures in Regions."
- ²⁵ Kappenman, *Geomagnetic Storms and Their Impact*, 3-26.
- ²⁶ NERC and U.S. DOE, *High Impact, Low Frequency Event*, 74.
- ²⁷ EMP Commission, *Critical National Infrastructures*, 27.
- ²⁸ Kappenman, *Geomagnetic Storms and Their Impact*, 4-18.
- ²⁹ Ibid.
- ³⁰ Ibid., 4-22.
- ³¹ Brown, *Electricity Transmission: A Primer*, 32.
- ³² EMP Commission, *Critical National Infrastructures*, 17.
- ³³ Ibid.
- ³⁴ Ibid., 19.
- ³⁵ U.S.-Canada Power System Outage Task Force, *Final Report on August 14, 2003 Blackout*, 1.
- ³⁶ EMP Commission, *Critical National Infrastructures*, 19.
- ³⁷ Ibid., 68.
- ³⁸ Ibid., 78 - 79.
- ³⁹ Ibid., 91.
- ⁴⁰ Ibid., 92.
- ⁴¹ Ibid.
- ⁴² Ibid., 103.
- ⁴³ Ibid.
- ⁴⁴ Ibid.
- ⁴⁵ Ibid., 107.

⁴⁶ Ibid., 110.

⁴⁷ Ibid., 113.

⁴⁸ Ibid.

⁴⁹ Ibid.

⁵⁰ Ibid., 126.

⁵¹ Ibid., 120.

⁵² Ibid., 129.

⁵³ Ibid.

⁵⁴ Ibid.

⁵⁵ Ibid., 136.

⁵⁶ Ibid., 139.

⁵⁷ Ibid.

⁵⁸ Ibid.

⁵⁹ Ibid., 143 - 144.

⁶⁰ Ibid., 149.

⁶¹ Ibid.

⁶² Ibid., 150.

⁶³ Ibid., 151.

⁶⁴ Ibid.

⁶⁵ Ibid.

⁶⁶ DHS, *National Response Framework*, 10.

⁶⁷ OCIEP, *Geomagnetic Storms*.

⁶⁸ U.S. DOE, *Smart Grid System Report*, 41.

⁶⁹ Ibid.



⁷⁰ *Transmission and Distribution World*, “Network to Provide Early Warning.”

⁷¹ U.S. DOE, *Smart Grid System Report*, 43.

⁷² DHS and U.S. DOE, *Energy Sector-Specific Plan*, 26.

⁷³ U.S. DOE, *Smart Grid System Report*, 6.

⁷⁴ EMP Commission, *Critical National Infrastructures*, 58.

⁷⁵ *Ibid.*

⁷⁶ *Ibid.*

⁷⁷ *Ibid.*, 59.

⁷⁸ *Ibid.*

⁷⁹ *Ibid.*

⁸⁰ Kappenman, *Geomagnetic Storms and Their Impact*, x.

⁸¹ *Ibid.*

⁸² Birnbach and Kappenman, *High Power Cold Cathode Electron Tubes*, 10.

⁸³ House, *What is Space Weather*, 32.

⁸⁴ National Research Council, *Severe Space Weather Events*, 56.

⁸⁵ Onsager and Viereck, “Space Weather Data and Observations,” slide 5.

⁸⁶ NOAA, “Advanced Composition Explorer.”

⁸⁷ MSNBC.com, “Sun-watching Probe Turns an Amazing 10.”

⁸⁸ NOAA, “National Environmental Satellite Service.”

⁸⁹ NERC and U.S. DOE, *High Impact, Low Frequency Event*, 74.

⁹⁰ *Ibid.*, 70.

⁹¹ EMP Commission, *Critical National Infrastructures*, 17.

⁹² *Ibid.*

⁹³ Kappenman, *Low Frequency Protection Concepts*, xi.

-
- ⁹⁴ EMP Commission, *Critical National Infrastructures*, 58.
- ⁹⁵ Ibid., 58.
- ⁹⁶ NERC, *2009 Long Term Reliability Assessment*, 30.
- ⁹⁷ Ibid.
- ⁹⁸ EMP Commission, *Critical National Infrastructures*, 49.
- ⁹⁹ Kappenman, *Geomagnetic Storms and Their Impact*, x.
- ¹⁰⁰ EMP Commission, *Critical National Infrastructures*, 60. Kappenman, *Low Frequency Protection Concepts*, xi.
- ¹⁰¹ National Research Council, *Severe Space Weather Events*, 69.
- ¹⁰² NOAA, "National Environmental Satellite Service."
- ¹⁰³ U.S. Department of Energy, *Smart Grid System Report*, 49.
- ¹⁰⁴ Odenwald, *The 23rd Cycle*, <http://www.solarstorms.org/Spower.html>.
- ¹⁰⁵ Kappenman, *Geomagnetic Storms and Their Impact*, x.
- ¹⁰⁶ EMP Commission, *Critical National Infrastructures*, 54.
- ¹⁰⁷ Schnurr, "NARUC Electricity and Critical Infrastructures," slide 8. Butt, "EMP Threat." Emanuelson, "Nuclear Electromagnetic Pulse."

Bibliography

- 2009 Long Term Reliability Assessment: 2009 - 2018*. Princeton, NJ: North American Electric Reliability Corporation, 15 December 2009. http://www.nerc.com/files/2009_LTRA.pdf.
- Albert, Reka, Istvan Albert, and Gary L. Nakarado. *Structural Vulnerability of the North American Power Grid*. Pennsylvania State University, 2004. http://arxiv.org/PS_cache/cond-mat/pdf/0401/0401084v1.pdf.
- Birnbach, Curtis, and John Kappenman. *High Power Cold Cathode Electron Tubes for Power Electronics Applications*. Seattle, WA: Advanced Fusion Systems, 2 November 2010. http://www.nsrp.org/Ship_Production_Panels/Electrical_Technologies/downloads/110210_High_Power_Cold_Cathode_Electron_Tubes_for_Power_Electronics_Applications_Birnbach.pdf.
- Brown, Matthew H., and Richard P. Sedano. *Electricity Transmission: A Primer*. Washington, DC: National Council on Electric Policy, June 2004. <http://www.puc.nh.gov/Transmission%20Commission/Transmission%20Infrastructure/Appendix%20A.pdf>.
- Butt, Yousaf. "The EMP Threat: Fact, Fiction, and Response (Part 2)." *The Space Review.com*, 1 February 2010. <http://www.thespacereview.com/article/1553/1>.
- Critical National Infrastructures*. Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. Washington, DC, April, 2008. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf.
- Emanuelson, Jerry. "Nuclear Electromagnetic Pulse." <http://www.futurescience.com/emp.html> (accessed 31 March 2011).
- Energy Sector-Specific Plan: An Annex to the National Infrastructure Protection Plan 2010*. Department of Homeland Security and U.S. Department of Energy. Washington, DC, 2010. <http://www.dhs.gov/xlibrary/assets/nipp-ssp-energy-2010.pdf>.
- Executive Brief: Electromagnetic Pulse and Geomagnetic Storm Events*. Princeton, NJ: North American Electric Reliability Corporation, 24 August, 2009. [http://www.nerc.com/fileUploads/File/CIP/EMP-Geomagnetic-Exec-Brief\(1\).pdf](http://www.nerc.com/fileUploads/File/CIP/EMP-Geomagnetic-Exec-Brief(1).pdf).
- Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendation*. U.S.-Canada Power System Outage Task Force. Washington, DC, April, 2004. <http://www.nerc.com/filez/blackout.html>.
- Gaunt, C.T. and G. Coetzee. "Transformer Failures in Regions Incorrectly Considered to Have LowGIC-Risk." <http://www.labplan.ufsc.br/congressos/powertech07/papers/445.pdf>.

Geomagnetic Storms - Reducing the Threat to Critical Infrastructure in Canada. Office of Critical Infrastructure Protection and Emergency Preparedness, 25 April 2002. <http://www.solarstorms.org/CanadaPipelines.html>.

High-Impact, Low-Frequency Event Risk to the North American Bulk Power System. A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop. Washington, DC, June 2010. <http://www.nerc.com/files/HILF.pdf>.

Kappenman, John. *Geomagnetic Storms and Their Impacts on the U.S. Power Grid.* Goleta, CA: Metatech Corporation, January 2010. http://www.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf.

Kappenman, John. *Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation.* Goleta, CA: Metatech Corporation, January 2010. http://www.futurescience.com/emp/ferc_Meta-R-322.pdf.

Lawrence, Joseph E. "The Solar 'Katrina' Storm That Could Take Our Power Grid Out For Years." *Huffington Post*, 15 July 2010. http://www.huffingtonpost.com/lawrence-e-joseph/the-solar-katrina-storm-t_b_641354.html.

Moteff, John, and Paul Parfomak. *Critical Infrastructure and Key Assets: Definition and Identification.* CRS Report for Congress RL32631. Washington, DC: Library of Congress, 2004. <http://www.fas.org/sgp/crs/RL32631.pdf>.

National Aeronautics and Space Administration. "Advanced Composition Explorer." <http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1997-045A>.

National Oceanic and Atmospheric Administration. "National Environmental Satellite Service: FY 2012 Budget Highlights." http://www.corporateservices.noaa.gov/nbo/fy12_budget_highlights/NESS_FY12_One_pager.pdf.

National Response Framework. Department of Homeland Security. Washington, DC, January 2008. <http://www.fema.gov/pdf/emergency/nrf/nrf-core.pdf>.

NERC System Disturbance Analysis: 1989 Geomagnetic Storm. Princeton, NJ: North American Electric Reliability Corporation, August 1990. <http://www.nerc.com/files/1989-Quebec-Disturbance.pdf>.

"Network to Provide Early Warning of Potential Disturbances in Regional Electric Grid for Western U.S. and Canada." *Transmission and Distribution World*, 19 July 2011. http://tdworld.com/test_monitor_control/highlights/harris-grid-warning-0711/index.html?imw=Y&utm_source=feedburner&utm_medium=feed&utm_campaign

=Feed%3A+td-most-read+%28T%26D+World%3A+Today%27s+Most+Read+Articles%29.

Odenwald, Sten. *The 23rd Cycle: Learning to Live with a Stormy Star*. Columbia University Press, 2000. <http://www.solarstorms.org/Spower.html>.

Onsager, Terrance G., and Rodney Viereck. "Space Weather Data and Observations at the NOAA Space Weather Prediction Center." National Oceanic and Atmospheric Administration Space Weather Prediction Center, 2011. <http://sidc.oma.be/esww7/presentations/3.4.ppt>.

Schnurr, Avi. "NARUC Electricity and Critical Infrastructures Committees: EMP and Geomagnetic Storms: Risk, Impact and Options." Electric Infrastructure Security Council, 2011. <http://www.narucmeetings.org/Presentations/NARUC%20EMP%20Presentation.pdf>.

Severe Space Weather Events – Understanding Societal and Economic Impacts. National Research Council Workshop Report. Washington, DC: National Academies Press, 2008. <http://www.nap.edu/catalog/12507.html>.

Smart Grid System Report. U.S. Department of Energy. Washington, DC, July 2009. http://www.smartgrid.gov/sites/default/files/resources/systems_report.pdf.

"Sun-watching Probe Turns an Amazing 10." MSNBC.com, 29 November 2005. http://www.msnbc.msn.com/id/10254710/ns/technology_and_science-space/t/sun-watching-probe-turns-amazing/.

US House. *What is Space Weather and Who Should Forecast It: Hearing Before the Subcommittee on Environment, Technology, and Standards*. 108th Cong., 1st sess., 2003.